Journal of Mechanical Engineering Research and Developments
ISSN: 1024-1752
Website: http://www.jmerd.org
Vol. 39, No. 1, 2016, pp. 88-96

Walking Gait Planning for a Kind of Humanoid Robot

H. P. Huang*, S. D. Xiao, & Z. B. Li

Electromechanical and Control Department, Mechanical Engineering College
Southwest Jiaotong University, Chengdu, Sichuan, 610031, P. R. China, *Email: hhping2@163.com

ABSTRACT: Gait planning is one of the important and difficult problems in the research of humanoid robot. In order develop a good walking gait planning solution for a kind of humanoid robot whose prototype has been design by us, an off-line gait planning method is proposed in this paper. First, the robot is simplified as an inverted pendulum model. Then we use this inverted pendulum model to do forward and lateral movement gait planning. Motion function of each joint angle has been determined. Finally, we use ZMP stability criterion to evaluate the gait planning solution. Evaluation results verifies that the gait planning method of humanoid robot proposed in this paper is reasonable and feasible, and it can ensure the steady walking of the humanoid robot.

KEYWORDS: Humanoid robot; Gait planning; Inverted pendulum; Zero Movement Point.

INTRODUCTION

Humanoid robot is not only an important symbol of national high-tech comprehensive level, but also has a wide range of application in human's production and life [1]. In order to realize the walking motion of the humanoid robot, we must exert a load on each joint of the robot to make the joint move according to the specific time sequence. How to obtain the time series motion function of each joint? The usual method is to use the theory of kinematics and dynamics to make the gait planning of humanoid robot [2]. Gait planning is one of the important and difficult problems in the research of humanoid robot, and the reasonable gait planning is one of the keys to the steady walking of humanoid robot. Some researchers have done relevant work in this field [3-5].

Gait planning is defined as a kind of coordination relationship between the joint movement in the time and space of the walking system under the condition of walking environment and gait parameters and ensuring the stability of the walking constraints [6,7]. The motion relationship of robot joints can be expressed as a function of time [8]. Research on gait planning of humanoid robot has many research methods, the current methods commonly used are: Based on gait planning ZMP (Zero Movement Point), based on a five bar linkage gait planning method and based on the inverted pendulum gait planning method [9]. The humanoid robot walking system is characterized by multi variable and high order nonlinear, which is very similar to the characteristics of the motion of inverted pendulum system. So, it is feasible to use the inverted pendulum model to research the gait planning problem of humanoid robot. In this paper, we use the gait planning method based on the inverted pendulum, which calculate the motion trajectory of ZMP by applying the given robot centroid trajectory.

The organization of the rest of this paper is as followed. In section II, we give an overview of the humanoid robot body structure that we designed. In section III, we discuss the forward gait planning of this robot. In section IV, we discuss the lateral gait planning problems. In section V, the gait planning is evaluated to verify the correctness of the results of the gait planning. In section VI, we give a conclusion and our future research directions.

HUMANOID ROBOT BODY STRUCTURE

Humanoid robot is the imitation of human body, but the body of a real human has a total of several hundreds of freedom degrees, it is impossible for us to control so many degrees of freedom of the multivariable system. Therefore, in the design of humanoid robot walking mechanism, we just consider the essential function for walking. In this paper, we design a humanoid robot model shown in Figure1. Its freedom degrees are configured as follows: 1 degree of freedom for the shoulder, 3 degrees of freedom for the elbow, two degrees of freedom for the wrist joint, 3 degrees of freedom for the hip joint, 1 degree of freedom for the knee joint, 2 degrees of freedom for the ankle joint. The design dimensions of each part of the robot are shown in the table1. In following sections, we will use this robot model structure and its design dimensions as the base data to discuss and calculate its gait planning problems.

DOI: 10.7508/jmerd.2016.01.013

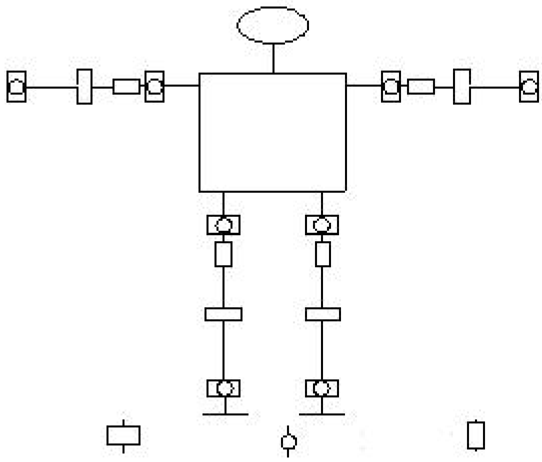

Figure 1. A humanoid robot model.

Table 1. The design dimensions of each part of the robot.

Items	Length(mm)
Head	240
Upper body	500
Long arm	220
Forearm	235
Upper leg	450
Lower leg	450

FORWARD GAIT PLANNING

Centroid motion planning of humanoid robot

According to the motion characteristics of humanoid robot, in this paper the humanoid robot model is approximated as a single inverted pendulum model, which is composed of a particle and a non - mass leg that connect this particle with the ankle joint. The model of the robot walking system is obtained by the simplified model of the inverted pendulum as shown in Figure2. The coordinate origin is the center of the rotation of the ankle joint.

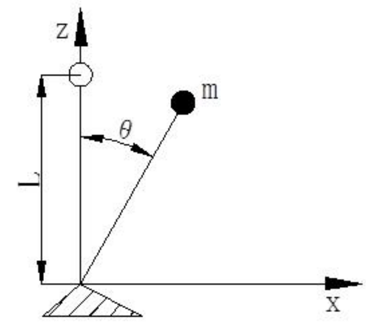

Figure 2. The inverted pendulum model of humanoid robot's forward motion.

The forward motion equation of humanoid robot is $ma_\tau = mg\sin\theta$, in which the tangential acceleration $a_\tau = l\ddot{\theta}$. So, we can get $ml\ddot{\theta} = mg\sin\theta$. Set $a = \sqrt{\frac{g}{l}}$, then by solving ordinary differential equations, we can get $\theta(t) = c_1 / e^{at} + c_2 e^{at}$. According to the characteristics of humanoid robot prototype model, set the robot walking parameters, step length $s = 0.4m$, single step cycle $T = 0.8s$, and the height of mass center of the robot $l = 1m$. Due to the periodicity and the symmetry of the movement of the left and right leg, we know that $\theta(0) = -\theta(t)$.

When t=0, according to the geometric relationship of the inverted pendulum, the initial condition of the robot's center of mass is obtained as $\theta(0) = -\arcsin(\frac{0.5s}{l}) = -0.2014$. So, $\theta(t) = 0.01792e^{3.1305t} - 0.21932e^{-3.1305t}$. Thus the centroid trajectory coordinate function is shown in equation (1).

$$\begin{cases} x = l\sin\theta = \sin(0.01792e^{3.1305t} - 0.21932e^{-3.1305t}) \\ z = l\cos\theta = \cos(0.01792e^{3.1305t} - 0.21932e^{-3.1305t}) \end{cases} . \tag{1}$$

Thus, the X direction trajectory and Z direction trajectory of the humanoid robot's centroid motion is obtained as shown in Figure3 and4:

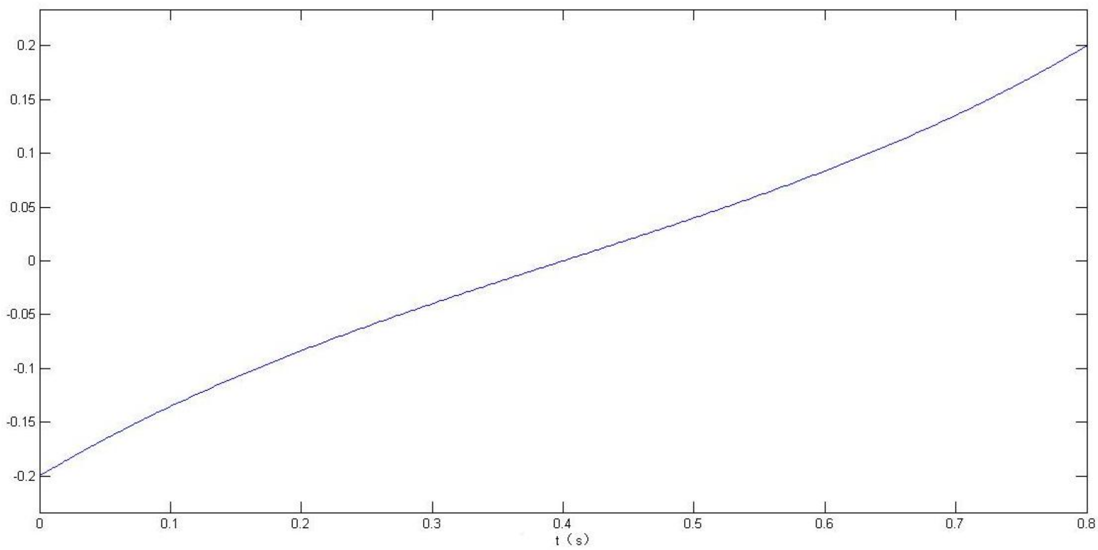

Figure 3. The motion trajectory of the humanoid robot centroid in X direction.

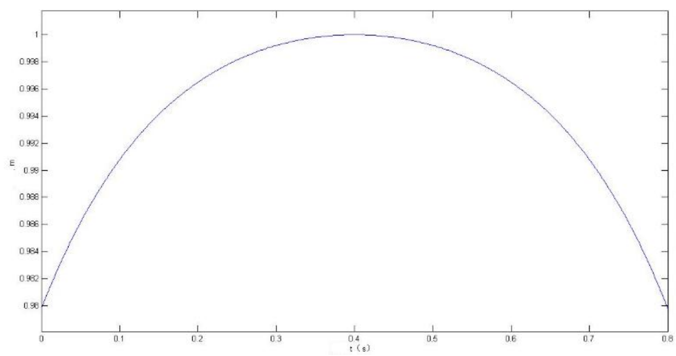

Figure 4. The motion trajectory of the humanoid robot centroid in Z direction.

Motion planning of humanoid robot swinging leg

During the motion of the swinging leg, the humanoid robot usually suffers a certain degree of shock impact in the process of leg raising and landing. In order to reduce the shock impact from the ground during the motion of the humanoid robot, and to avoid the abrupt change of the driving force in the process of the robot movement, the two order derivative continuous curve is used to track the trajectory of the swing leg. In this way, the acceleration of the swinging leg movement is changed continuously, and the speed curve is smooth. In addition, the lifting height of the humanoid robot's swing leg has great influence on the obstacle avoidance ability of humanoid robot. So considering comprehensively above-mentioned factors, in this paper, we use the five spline curve of polynomial interpolation to track the trajectory of the swing leg, and the following describes the motion planning of the swing leg in X direction and Z direction.

Motion planning of the swing leg in X direction

During [0, Td], the humanoid robot is in a two foot support phase. Take the support point as the origin of the coordinates, we know that the position of the swing leg at this time is -s, $x_a(t) = -s, t \in [0, T_d]$. During [Td, T], the constraint condition of the swing leg in X direction is:

$$\begin{cases} x_a(T_d) = -s \\ x_a(T) = s \\ x_a'(T_d) = 0 \\ x_a'(T) = 0 \\ x_a''(T_d) = 0 \\ x_a''(T) = 0 \end{cases}$$

According to the initial condition, the solution of differential equation is

$$x_a(t) = -0.4128 + 0.5080\mathrm{t} - 6.9851\mathrm{t}^2 + 37.3067\mathrm{t}^3 - 54.5709\mathrm{t}^4 + 24.8050\mathrm{t}^5$$

So, the mathematical expression for the motion trajectory of the swing leg in X direction is shown in equation (2), and the trajectory figure is shown in Figure5.

$$\begin{cases} x_a = -s & t \in [0, T_d] \\ x_a = -0.4128 + 0.5080\mathrm{t} - 6.9851\mathrm{t}^2 + 37.3067\mathrm{t}^3 - 54.5709\mathrm{t}^4 + 24.8050\mathrm{t}^5 & t \in [T_d, T] \end{cases} \quad (2)$$

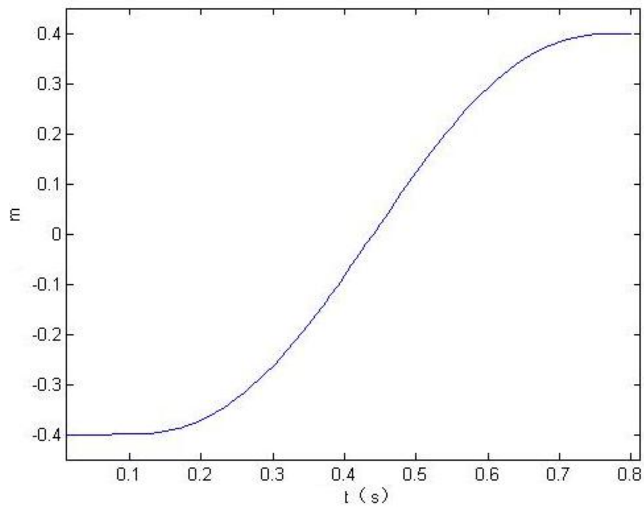

Figure 5. The motion trajectory of the swing leg in X direction.

Motion planning of the swing leg in Z direction

In the motion planning of the swing leg in Z direction, to fully consider the robot's ability to avoid obstacles, we suppose that in the middle time of the motion cycle of the swing leg $t = \frac{T + T_d}{2}$, the swing leg reaches the maximum height H_f=0.14m. In order to make the swing leg move smoothly and without shock impact in Z direction, we divide the motion trajectory into three parts: the stationary state of the double foot supporting stage, the smooth elevation stage and the smooth falling stage.

When the humanoid robot is in the stage of double foot supporting state, the Z coordinate of the swing leg does not change, so $z_a = 0.14 \quad m \quad t \in [0, T_d]$. When the swing leg of humanoid robot is in the stage of smooth elevation stage $t \in [T_d, (T+T_d)/2]$, the motion constraint equation of swing leg is

$$\begin{cases} z_a(T_d) = H_f \\ z_a((T+T_d)/2) = H_f + H_a \\ z_a'(T_d) = 0 \\ z_a'((T+T_d)/2) = 0 \\ z_a''(T_d) = 0 \\ z_a''((T+T_d)/2) = 0 \end{cases}$$

Similarly, when the swing leg of humanoid robot is in the stage of smooth falling stage $t \in [T_d,(T+T_d)/2]$, the motion constraint equation of swing leg is

$$\begin{cases} z_a((T+T_d)/2) = H_f + H_a \\ z_a(T) = H_f \\ z_a'(T) = 0 \\ z_a'((T+T_d)/2) = 0 \\ z_a''(T) = 0 \\ z_a''((T+T_d)/2) = 0 \end{cases}$$

By solving the constraint equation, we get the function for the swing leg motion trajectory in Z direction as shown in equation (3). The motion trajectory figure is shown in Figure 6.

$$\begin{cases} z_a = 0.14 & t \in [0, T_d] \\ z_a = 0.1283 + 0.4904t - 7.2438t^2 + 44.9572t^3 - 102.8950t^4 + 79.1500t^5 & t \in [T_d, (T+T_d)/2] \\ z_a = 5.6676 - 49.1795t + 173.2459t^2 - 296.5757t^3 + 246.0880t^4 - 79.3832t^5 & t \in [(T+T_d)/2, T] \end{cases} \quad (3)$$

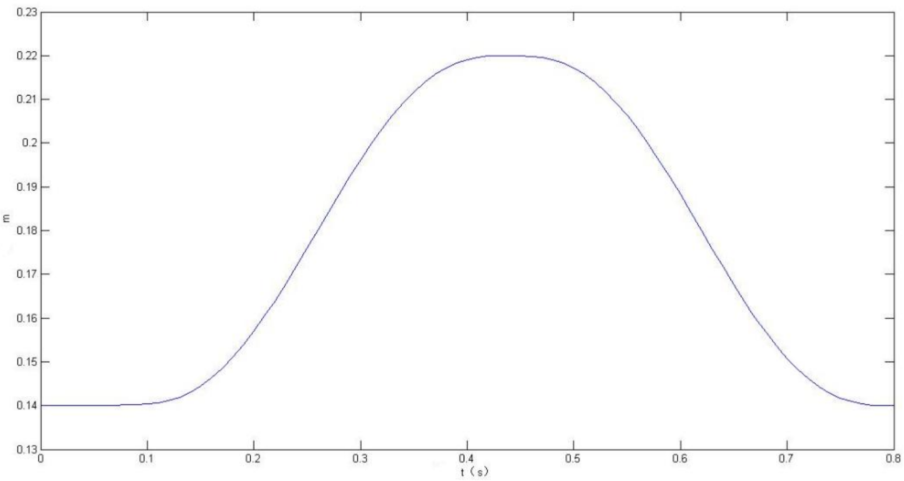

Figure 6. The motion trajectory of the swing leg in Z direction.

Calculate the joint angles of supporting leg

According to the prototype of humanoid robot, the joint angles of the robot support leg are simplified as shown in Figure 7.

By using the centroid trajectory (X_C, Z_C) of humanoid robot which has been calculated as mentioned above, as well as the geometric relationship of humanoid robot leg, we know the joint angles of robot legs are as follows: $\theta_a = \alpha_a + \alpha$, $\theta_k = \pi - \alpha_k$, $\theta_h = \alpha_h - \alpha$.

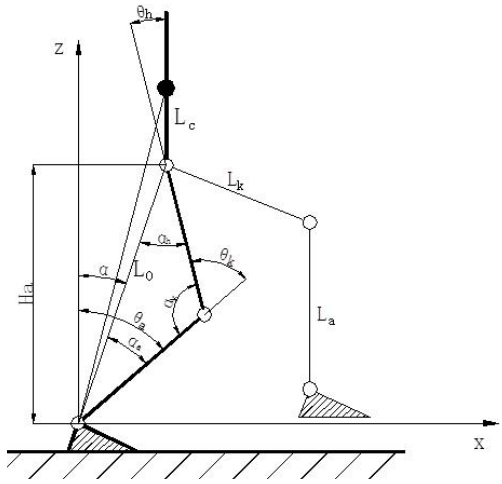

Figure 7. Geometry diagram of the humanoid robot's supporting leg.

Calculate the joint angles of swing leg

The humanoid robot swing leg structure is simplified, as shown in Figure 8.

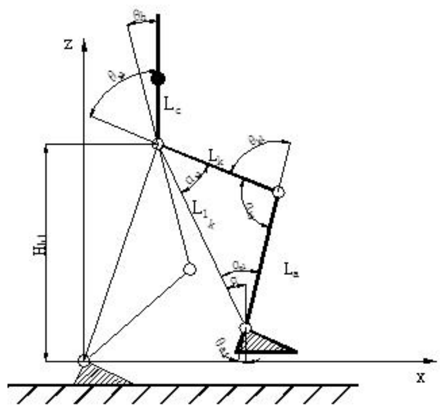

Figure 8. Geometry diagram of the humanoid robot's swing leg.

According to the geometric relationship of the humanoid robot's swing leg, as well as the centroid trajectory (X_C, Z_C) and the ankle joint motion trajectory (Xa, Za) that have been calculated before, the trajectory of the hip, knee and ankle joints can be finally determined as follows: $\theta_{a1} = a_{a1} - a$, $\theta_{k1} = \pi - a_{a1}$, $\theta_{h1} = a_{a1} + a$.

It should be noted that the above calculation for centroid motion trajectory of the of the humanoid robot, the trajectory of the ankle joint, the joint angles of the supporting leg and the swing leg are all limited in a single walking cycle. So, we must plan the trajectory of the given time period to make the humanoid robot walk a distance. By using the symmetry of the left and right leg as well as the periodicity when the robot is walking, we can do the translation of the single cycle track on the time axis. In this way, the trajectory of the joint angles of the humanoid robot is obtained.

LATERAL GAIT PLANNING

Centroid lateral motion planning

In the humanoid robot walking process, the robot centroid lateral motion planning is similar to forward motion planning, the schematic diagram is shown in Figure 9.

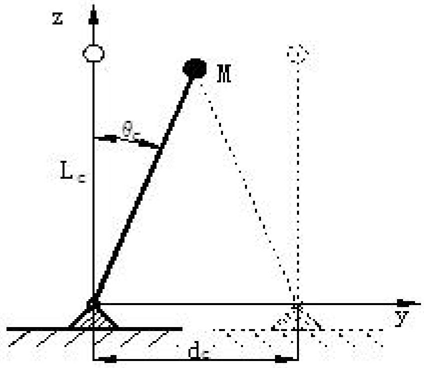

Figure 9. The inverted pendulum model of the robot centroid lateral movement.

According to the geometric shape of humanoid robot, the lateral distance of the center of the two feet is dc=0.141234m. Due to the modeling of the robot, the vertical height of the forward rotating ankle joint and the lateral ankle joint are not coincident. After measurement, we know that when the centroid of the robot is in the lateral movement, the distance between the lateral ankle joint and centroid of the robot is Lc=0.955m. Motion equation of the centroid lateral movement angle θ is $\theta_c(t) = c_1 / e^{at} + c_2 e^{at}$.

As the humanoid robot moves in the forward direction, the swing leg and the supporting leg are in the plane of the YOZ plane, and the robot centroid is located on the top of the supporting leg. In the lateral motion planning of the centroid, we specify this time is the initial moment of the centroid lateral movement for convenient calculation. As we know, at the moment t=0, the movement speed is zero. When the humanoid robot moves to T/2, the robot can reach the situation as shown in Figure 9.

According to the geometric relations available at this time, we know that $\theta_c(T/2) = \arcsin(\frac{d_c/2}{L_c})$. In combination with the initial condition of the lateral motion of the humanoid robot, the constraint equation is: $\begin{cases} \theta_c(0)' = 0 \\ \theta_c(T/2) = \arcsin(\frac{d_c/2}{L_c}) \end{cases}$. After solving the differential equation, we get the angular motion function for centroid lateral movement in the time period of [0,T/2], it is $\theta_c(t) = 0.0182e^{3.2034t} + 0.0182e^{-3.2034t} \quad t \in [0, T/2]$.

During the time period of [T/2,T], the original swing leg has changed to act as the supporting leg, and the original supporting leg has changed to act as the swing leg, thus to form a new inverted pendulum. According to the symmetry of walking motion, we get $\theta_c(t) = 0.0182e^{3.2034(T-t)} + 0.0182e^{-3.2034(T-t)} \quad t \in [T/2, T]$.

In order to realize the movement of the whole gait cycle of the humanoid robot, it is necessary to repeat the movement cycle of the swing leg to the position of the initial moving leg. So here, continue to plan the next cycle of movement:

$\theta_c(t) = 0.0182e^{3.2034(t-T)} + 0.0182e^{-3.2034(t-T)} \quad t \in [T, 3T/2]$,

$\theta_c(t) = 0.0182e^{3.2034(t-T)} + 0.0182e^{-3.2034(t-T)} \quad t \in [T, 3T/2]$

The diagram for centroid lateral movement angle θ is shown in Figure10.

Similar to forward motion, the centroid motion trajectory of lateral movement can be calculated according to the relationship between the centroid and the angle of rotation: $\begin{cases} y_c = L_c \sin\theta_c \\ z_{c1} = L_c \cos\theta_c \end{cases}$.

Calculation for joint angle of robot lateral motion planning

In order to keep the stability of walking, the movement of the robot's upper body must be very little in the process of walking. In the motion planning process, this article supposes that the robot upper body maintain vertical, the feet maintain level to the ground. When the humanoid robot keeps the lateral movement, only the hip joint and the ankle joint have the freedom of lateral swing. According to the geometrical characteristic and the degree of freedom of the humanoid robot, the joint angle of the lateral motion is simplified, as shown in Figure 11.

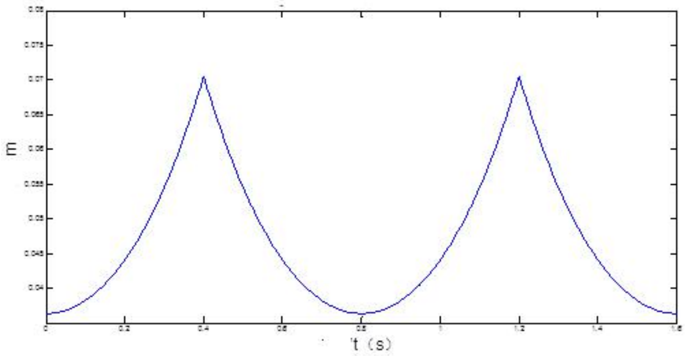

Figure 10. The diagram for centroid lateral movement angle θ.

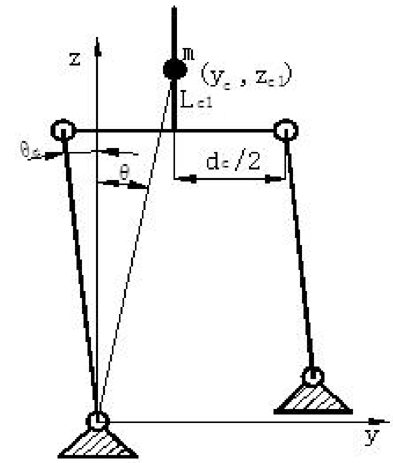

Figure 11. Schematic diagram of the lateral movement joint of humanoid robot.

According to the geometric shape of the humanoid robot, the vertical distance between the center of mass and the hip joint is obtained by measuring, $L_{c1} = 0.25 \quad m$. The geometric relation of lateral joint is described as the following equation: $\theta_c(t) = \arcsin(\frac{d_c/2 - y_c}{l_{leg}})$. According to the geometric relationship, the lateral trajectory of the ankle joint is the same as that of the lateral movement of the hip joint, both of which are shown in Figure12.

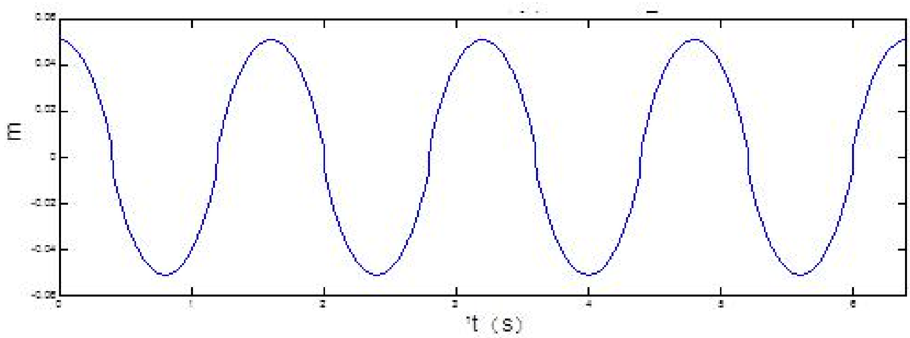

Figure 12. Lateral movement trajectory of the ankle joint and the hip joint.

WALKING STABILITY EVALUATION OF HUMANOID ROBOT

Any practical robot system always move or work in an environment with a variety of occasional or continuous interference, humanoid robots are no exception. In order to ensure that the humanoid robot in the case of interference is still in accordance with the expected situation, then we need to make it to meet the walking stability requirements. The judgment basis for walking stability of humanoid robot mainly includes ZMP stability criterion, Poincare recurrence theorem, and Angular momentum criterion of center of mass.

In this paper, a method based on ZMP stability criterion is used to evaluate the walking process. The so-called ZMP (zero moment point) is the intersection of the resultant force composed of gravity and inertia force with the ground. According to the ZMP stability criterion, if we want to keep the humanoid robot stable during the walking motion, then we should ensure that the ZMP is inside the support polygon when the humanoid robot is in walking process. The support polygon is the minimum polygon area on which the two feet of the humanoid robot contact with the ground. The basic calculation formula of ZMP is simplified as equation (4) when we considering an inverted pendulum model.

$$\begin{cases} x_{zmp} = \dfrac{m(\ddot{Z}+g)X - m\ddot{X}Z}{m(\ddot{Z}+g)} \\ y_{zmp} = \dfrac{m(\ddot{Z}+g)Y - m\ddot{Y}Z}{m(\ddot{Z}+g)} \end{cases}$$

Apply the centroid trajectory of forward and lateral movement in equation (4) to calculate the position of ZMP, the result is (0,0). This result means that, in the process of walking motion, ZMP is always in the coordinate origin, so that the gait planning method of humanoid robot proposed in this paper is reasonable and feasible.

CONCLUSION

Gait planning is one of the important and difficult problems in the research of humanoid robot, and the reasonable gait planning is one of the keys to the steady walking of humanoid robot. An off-line gait planning method is proposed in this paper. After considering the geometric characteristics of the humanoid robot model we designed, it is simplified as an inverted pendulum model. Then we use this inverted pendulum model to do gait planning. The main work include forward and lateral movement gait planning. Motion function of each joint angle has been determined. Finally, the gait planning is evaluated according to the ZMP stability criterion, and the correctness of the gait planning results is finally verified.

CONFLICT OF INTEREST

The author confirms that this article content has no conflict of interest.

ACKNOWLEDGEMENTS

We acknowledge that our work is supported by the Sichuan Application Fundamental Research Funds (No. 2014JY0212).

REFERENCES

[1] Zhangtao. Robot Introduction. Beijing: China Machine Press, 2010.

[2] Xiao Nanfeng. Humanoid Robot. Beijing: Science Press, 2008.

[3] Yu Chaoyan. Research on gait planning of biped walking robot. Harbin Engineering University 2007.

[4] Wei Hangxin, Liu Mingzhi, Zhao Liqin. Simulation of running motion of humanoid robot. Journal of System Simulation, 2007, 19(2): 396-399.

[5] Ke Xianxin. Research on biped dynamic walking of humanoid robot. Shanghai: Shanghai University, 2005.

[6] Lyapunov A M. The general problem of the stability of motion. International Journal of Control. 1992, 55(3): 531-773.

[7] Li Q, Taksnishi A, Kato I. Learning control of compensation trunk motion for biped walking botor based on ZMP stability criterion //Proceedings of IEEE Int Conf on Robotics System, Yokohama, 1992:597-603.

[8] Seungsu Kim, ChangHwan Kim, Bumjae You, et a1. Stable Whole body Motion Generation for Humanoid Robots to Imitate Human Motions. The 2009 IEEE/RSJ International Conference on Intelligent Robots and Systems.2009: 2518-2524.

[9] LEE B J, Stonier D, XIM Y D, et a1. Modifiable Walking Pattern Generation Using Real-time ZMP Manipulation for Humanoid Robots.Proceedings of the 2007 IEEE/RSJ International Conference on Intelligent Robots and Systems.2007: 4221-4226.